

Available online at www.sciencedirect.com**ScienceDirect**

Procedia Materials Science 4 (2014) 269 – 273

Procedia
Materials Sciencewww.elsevier.com/locate/procedia

8th International Conference on Porous Metals and Metallic Foams, Metfoam 2013

Monotonic and cyclic loading behavior of closed-cell aluminum foams and sandwich structures

Srecko Nesic*, Ulrich Krupp, Wilhelm Michels

Institute for Materials Design and Structural Integrity, Faculty of Engineering and Computer Science, University of Applied Sciences Osnabrück, Albrechtstraße 30, 49076 Osnabrück, Germany

Abstract

Despite the fact that most aluminum foam products are used mainly due to their energy-absorption and damping capabilities, the respective Al-foam-containing structures may undergo fatigue damage to some extent. The present paper reviews the general issues of cyclic loading behavior of cellular metals, including their particular sensitivity to tensile loads. It was shown that nearly all aluminum foam products show poor ductility during testing. Correspondingly, fully-reversed rotating-bending tests on ALPORAS and FOAMTECH specimens revealed fatigue strength values at 10^7 cycles of only 10 % of the respective tensile strength. The deformation mechanisms of the aluminum metal foams have been further analyzed for various stress ratios, $R=-1$, $R=0.1$ and $R=10$ under uniaxial loading using an optical 3D strain analysis system (ARAMIS by GOM). The strain analysis system allows identifying positions of strain localization and ongoing fatigue damage. Fracture surfaces were analyzed by scanning electron microscopy (SEM). It has been found that morphological and microstructural defects, like relative large pores, silicon precipitates and grains within the cell walls lead to crack initiation and promote easy fatigue crack propagation and cell-wall fracture. The results are discussed within the scope to provide design guidelines for fatigue-loaded aluminum-foam-including structures.

© 2014 Elsevier Ltd. This is an open access article under the CC BY-NC-ND license

(<http://creativecommons.org/licenses/by-nc-nd/3.0/>).

Peer-review under responsibility of Scientific Committee of North Carolina State University

Keywords: Closed cell Al-foams; sandwich structures; monotonic testing; cyclic testing; digital image correlation; local strain distribution

1. Introduction

Cellular metallic materials have due to their unique structure a high potential for various light-weight, damping, heat-insulating, or energy-absorbing applications. Especially the subgroup of metal foams is often mentioned in

* Corresponding author. Tel.: (+49) (0)541/ 969 7023; Fax: (+49) (0)541/ 969 7047

E-mail address: s.nesic@hs-osnabrueck.de

literature to have a strong potential as energy absorber material (Gassan et al. (2001) and Handssen et al. (2002)), e.g., in cars, trains, or nuclear waste containers. Due to the high stiffness-to-density ratio, there is additional potential of these materials among lightweight applications as shown by Simancik (2001) and Banhart (2013). In the design of components with metal foam parts, the behavior of the foams under various loading conditions must be known. An inadequate analyzed field is the detailed response of metal foams to fatigue loading. In one of the first studies of this type, Zettl et al. (2000, 2001) described the fatigue properties between 10^4 cycles LCF (Zettl et al. (2001)) and 10^9 cycles VHCF (Zettl et al. (2000)) of various aluminum foams under fully reversed loading conditions using an ultrasonic fatigue testing equipment. They were able to correlate fatigue life with the strain amplitude and found that usually the cracks initialize in small holes or pre-existing cracks in the cell walls or cell walls, which are thinner than the average. In addition to this, Pinto et al. (2011) developed a damage accumulation model to describe the behavior of aluminum foams at fully reversed loads. However, the limitation of these previous studies is the monitoring of fatigue damage during the fatigue experiments, especially the local strain distribution on the sample surfaces. One of the few works in this field is the analysis of the tension-compression fatigue behavior of aluminum foam by Ingraham et al. (2009). They had shown that the crack propagation in fully reversed fatigue tests was assisted by compressive plastic deformation of the sample. The present paper shows first experiments of an analysis to close this gap and thus contribute to further understanding of the damage mechanisms during fatigue loading of metal foams. For this purpose, aluminum metal foams have been tested under uniaxial loading during various stress ratios in combination with a three-dimensional digital image correlation system (ARAMIS by GOM) to evaluate the development of local damage on the sample surfaces. In addition, the fracture surfaces of the cyclic deformation samples are analyzed for a correlation of microscopic defects and sample failure.

2. Materials and experiments

The metal foam samples of the cyclic tests consisted of Alporas (Shinko Wire Ltd.) and Foamtech (Foamtech Korea) material. Both were produced according to the Alporas procedure with 1.5 wt-% Ca and 1.6 wt-% TiH_2 as foaming agents. The average density of the Alporas samples was 0.28 g/cm^3 and the average density of the Foamtech samples was 0.29 g/cm^3 . Additionally, sandwich samples from the manufacturer Pohltec Metalfoam GmbH (material „Alulight AFS“ – AlMg6Si6 foam core with A6082 Al sheet, 11 mm core thickness and 1 mm sheet thickness) and the manufacturer Fraunhofer IWU (material „IWU“ – AlMg1Si0.8 foam core with S235 steel sheet, 16 mm core thickness and 2 mm sheet thickness) were exposed to quasi-static loads.

Except for the quasi-static compressive and bending tests, it was necessary to glue the samples with a two-component epoxy adhesive to the grips so that the tensile force could be applied to the samples.

The quasi-static compression tests were conducted according to the standards DIN 50134, (2008) and ISO/DIS 13314, (2011), while the basis for the bending tests was the standard DIN 53293, (1982) and the shear tests DIN 53294, (1982) (DIN = German Institute of Standardization). Accordingly, the samples for the rotating bending tests had a dog-bone shape DIN 50113, (1982). Due to the general requirement of 10 pores in each direction, the differing geometry of the foam samples was 80 mm in length, with a diameter of $\varnothing 40 \text{ mm}$ reduced to $\varnothing 30 \text{ mm}$ in the waisted area. The uniaxial tests were conducted on a 25 kN MTS testing machine at 25 Hz and various stress ratios $R=0.1$, $R=-1$ and $R=10$. The rotating bending fatigue tests were conducted on a Carl Schenck Simplex PUPN rotating bending machine at 26.5 Hz. For the analysis of local strains during the experiments, the optical strain measurement system ARAMIS 3D 5M (GOM GmbH, Germany) was used. A detailed description of the quasi-static tests and results are described elsewhere (Nesic et al. (2012)). They are used as basis for the fatigue tests and for comparison purposes. The analysis of fracture surfaces was conducted with analytical scanning electron microscopy (SEM Zeiss Auriga).

3. Results and discussion

3.1. Monotonic tests

The analysis of metal foams at monotonous loads was the prerequisite for further investigations applying cyclic loading. Hence, in a first step all materials were tested in tension, compression, bending and shearing. For each test

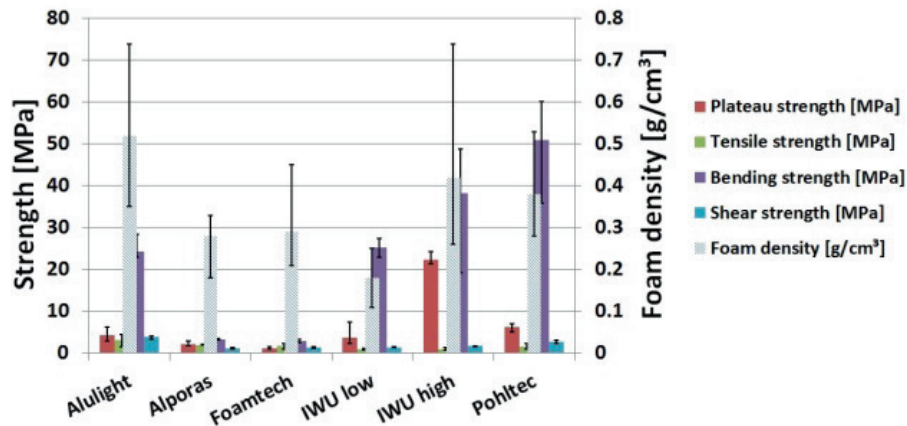


Fig. 1: Diagram showing the average density and strength values of the materials for the various monotonic tests

and each material between 4 and 7 samples were tested, corresponding to the compression test standard. An overview of the various materials and the respective most important values are shown in Fig. 1.

In the next step the values of these tests were used to adjust the initial stress values for the fatigue testing program, the first results of which are presented below.

3.2. Rotating bending tests

The results of the rotating bending fatigue tests, which were only be conducted with pure metal foam samples due to the experimental set-up and the required sample geometry, are shown in Fig. 2. Due to the fact that during rotating bending tests the sample undergoes both tensile and compressive loads (stress ratio $R=-1$) this experiment is a suitable and cheap alternative to uniaxial fatigue testing using servo-hydraulic or resonance testing systems. The stresses were chosen in such a way that they were significantly lower than the yield strength obtained from the quasi-static tests.

An analysis of the Wöhler diagram (Fig. 2) reveals that the fatigue life of the samples decreases gradually when increasing the load amplitude, however within a substantially large scatter band. The latter can be attributed to inhomogeneities of the sample material, e.g., big pores in the waisted area. In addition, micro-cracks, which can already occur during the manufacturing or cooling process in the pore walls, have an accelerating effect on the crack propagation as shown by Hupfer (2003). It was observed that micro-cracks can coalesce to a large crack which then causes final failure.

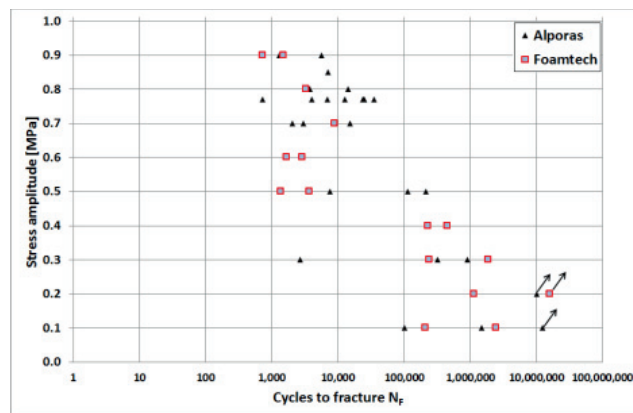


Fig. 2: Wöhler diagram of the rotating bending fatigue tests of Alporas and Foamtech samples

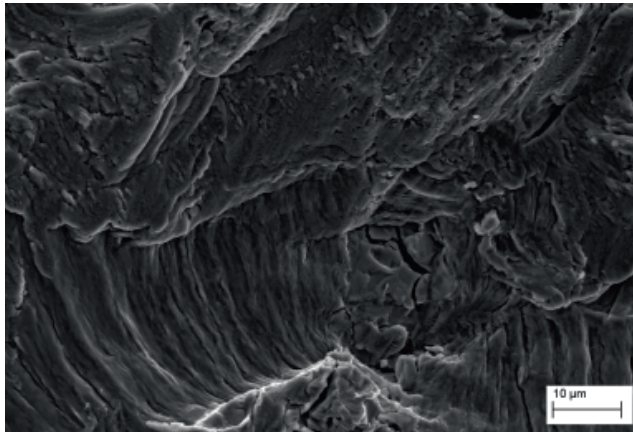


Fig. 3: Fracture surface of cell node after rotating bending fatigue test with fatigue striations after $N_f=5,700$ cycles

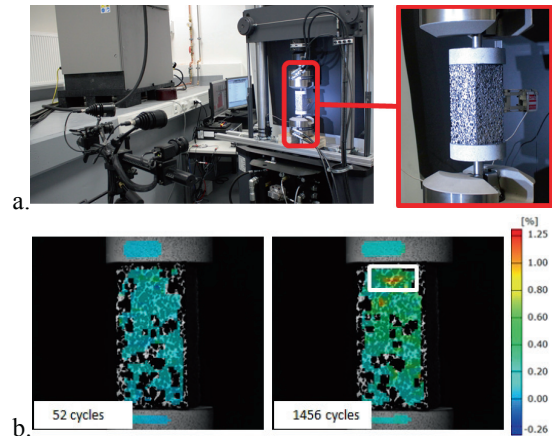


Fig. 4: a) Experimental set-up for uniaxial fatigue tests with DIC, b) Local strain distribution (major strain displayed in color) after 52 and 1,456 cycles of uniaxial tensile fatigue loading of an Alporas sample (failure after 1,509 cycles)

The highest stresses during bending occur naturally on the sample surface, so that the majority of cracks are originated here. Hence, it was observed that prior to failure the sample structures were held together only by some cell walls in the middle of the sample. An analysis of the fracture surfaces, which mainly run along the largest pores, reveal partly dimple fracture (ductile rupture) with particularly large Ca, Ti and Si particles, and at the same time fatigue striations (see Fig. 3). The cell walls in the middle of the sample show only ductile rupture. The low fatigue strength results also from the fact, that a large pore provides less material as compared to many small pores for the distribution of the load. Thus, the highest local stress values appear on the cell walls surrounding big pores. Here, fatigue striations are scarce, so that one can assume that the crack grow stepwise by ductile rupture of one or a few cell walls during only a few cycles.

3.3. Digital image correlation of uniaxial fatigue tests

The digital image correlation (DIC) was carried out using two 5 megapixel cameras arranged in an angle of 25 degrees to get three-dimensional displacement and strain data. The imaged displacements of the sample surface were analyzed with the ARAMIS software by GOM GmbH. The accumulated strain on the surface was visualized by comparison of a reference image of an unloaded sample with an image of the loaded sample close to the sample failure. Fig. 4 shows the surface strain distribution of an Alporas sample at two different stages during tension-tension fatigue loading ($R=0.1$, $\Delta\sigma/2 = 0.675$ MPa). The left image of Fig. 4 shows already strain concentrations at the surface after 52 cycles. From the beginning of the test these strain concentrations exhibit much higher strain values than the average value. During the test, these local strain concentrations intensify, finally leading to fatigue crack initiation. The main crack occurs in an area with the highest strain of approximately $\epsilon=1.2\%$, while the rest of the sample develops local strain values of $\epsilon=0.05$ till 0.2% .

Similarly, the local strain distribution of a Foamtech sample after compression-compression fatigue loading is shown in Fig. 5. One can see the development of high local strains (Fig. 5a) where the foam is compacted disproportionately high as compared to the rest of the sample surface. After collapse of this high strain area, new areas with a high local strain value are formed (Fig. 5b) until final failure by total densification of the specimen.

Although the observed open pores on the edge of the samples can be seen as artificial defects compared to samples with a foaming skin, this method of local deformation analysis is very suitable for an analysis of the metal foam itself while samples with a foaming skin should be seen as components according to DIN 50134, (2008).

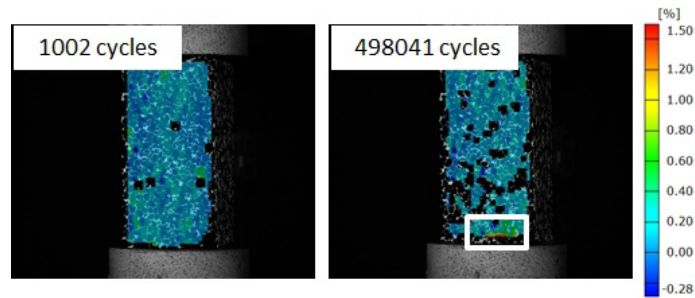


Fig. 5. Local strain distribution (major strain displayed in color) after 1,002 and 498,041 cycles of uniaxial compression fatigue loading of a Foamtech sample.

4. Conclusion

The analysis of different monotonic and cyclic loading arrangements leads to a better understanding of the metal foam behavior, which is a prerequisite for engineering design with these materials. Especially the strain distribution analysis via digital image correlation showed the inhomogeneous stress/strain reaction of metal foams to fatigue loading. This inhomogeneous strain distribution is observed for compressive and tensile fatigue loading, respectively. The results can lead to an easier adjustment of the foams to the individual application and in accordance to the expected load. A future step should be the definition of design guidelines for metal foam components.

Acknowledgements

The financial support by the German Ministry of Education and Research (BMBF) under grant no. FH PROFUND1751x09 and the dissertation fellowship of the University of Applied Sciences Osnabrück are gratefully acknowledged.

References

- Banhart, J., 2013. Light-Metal Foams – History of Innovation and Technological Challenges, *Advanced Engineering Materials*, 15, p. 82.
- DIN 50113: Testing of metallic materials – Rotating bending fatigue test.
- DIN 50134: Testing of metallic materials – Compression test of metallic cellular materials.
- DIN 53293: Testing of sandwiches – Flexure test of flat sandwiches.
- DIN 53294: Testing of sandwiches – Shear test in flatwise plane.
- Gassan, J., Harwick, W., Girlich, D., 2001. Behavior of aluminum foams under quasi-static and crash loadings, *Journal of Material Science Letters*, 20, p. 1047.
- Handssen, A. G., Langseth, M., Hopperstad, O.S., 2002. Crash Behavior of Foam-based Components: Validation of Numerical Simulations, *Advanced Engineering Materials*, 4, p. 771.
- Hupfer, K., 2003. Einfluss der Mikrostruktur auf die Festigkeitseigenschaften von Metallschäumen, Doctorate thesis, Technische Universität Braunschweig.
- Ingraham, M. D., DeMaria, C. J., Issen, K. A., Morrison, D. J., 2009. Low cycle fatigue of aluminum foam, *Materials Science and Engineering A*, 504, 150-156.
- ISO/DIS 13314: Mechanical testing of metals – ductility testing – Compression test for porous and cellular metals.
- Nesic, S., Unruh, K., Michels, W., Krupp, U., 2012. Mechanical Testing and Finite Element Simulations for the Use of Cellular Metals as Car Seat Components, *Steel Research International*, Vol. 83, p. 972.
- Pinto, H., Arwade, S. R., 2011. Damage accumulation model for aluminium-closed cell foams subjected to fully reversed cyclic loading, *Fatigue and Fracture of Engineering Materials and Structures*, 34, p. 1021.
- Simancik, F., 2001. Metallic foams – ultra light materials for structural applications, *Inzynieria Materialowa*, 5, p. 823.
- Zettl, B., Mayer, H., Stanzl-Tschegg, S. E., 2001. Fatigue properties of Al-1Mg-0.6Si foam at low and ultrasonic frequencies, *International Journal of Fatigue*, 23, p. 565.
- Zettl, B., Mayer, H., Stanzl-Tschegg, S. E., Degischer, H. P., 2000. Fatigue properties of aluminium foams at high numbers of cycles, *Material Science and Engineering*, A292, p. 1.